e040063

(2)

ExperCAT: An Expert System for Analysis and Short-Term Prediction of Clear Air Turbulence

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ABSTRACT

An expert system approach to the analysis and short-term prediction of clear air turbulence (CAT) is presented. CAT is defined here as nonconvective turbulence occurring above 18,000 feet. ExperCAT is rule-based, contains a total of 65 rules and has extensive help and explanation features. The system's analysis procedure is to guide a human observer in identifying cloud signatures known to be associated with CAT. ExperCAT forecasts include an estimate of the turbulence intensity and a confidence factor. The user can optionally view the selections entered to arrive at the forecast. Three step-by-step example runs are provided.

ACKNOWLEDGMENTS

The author acknowledges the support of the Project Manager, the Naval Ocean Systems Center (NOSC), Code 54, Dr. J. H. Richter, Program Element 62435N, and the Program Sponsor, the Office of Naval Technology, Mr. J. Cauffman, for making this effort possible. Dr. Gary Ellrod of the Satellite Applications Laboratory at NOAA/NESDIS developed the original decision tree upon which this work is based.

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1. Introduction

Clear air turbulence (CAT) is nonconvective turbulence that occurs at altitudes above 18,000 feet. The analysis and prediction of CAT is a difficult problem because it exists in relatively small areas and tends to change rapidly with time. The ability to analyze and forecast CAT requires a highly specialized, and therefore rare, expertise. Because it is a mesoscale phenomenon, CAT is difficult to diagnose by using relatively coarse (horizontal and temporal) resolution upper-air data measurements. For this reason, the focus of turbulence detection has shifted to the use of satellite imagery. Geostationary satellites are able to provide enough temporal and spatial resolution to detect CAT-producing conditions, assuming that such conditions can be related to cloud signatures seen on the image.

In a limited sense, diagnosis of turbulence based on cloud patterns is accomplished by the Satellite Image Analysis Meteorological Expert System (SIAMES) (Peak, 1989). SIAMES was developed using the expertise contained in the Navy Tactical Applications Guides (e.g., Fett et al., 1984). Turbulence is only one of many atmospheric parameters diagnosed during a SIAMES consultation session.

One of the foremost researchers of the relationship between CAT and cloud signatures is Dr. Gary Ellrod of the Satellite Applications Laboratory at NOAA/NESDIS. His latest report (Ellrod, 1989) contains a decision tree based on subjective techniques developed over the past ten years at the Satellite Applications Laboratory. The availability of this clear and concise

presentation of his extensive CAT expertise has led NOARL to propose an expert system for analysis and short-term prediction of CAT. The Ellrod decision tree was to provide the bulk of the expertise for the prototype system, and additional information from sources such as the NTAGs and a U.S. Air Force technical report were to be used to expand the prototype. For more information on expert systems, the reader is referred to the background presented in Peak and Tag (1989).

In this report, the development of this expert system, called "ExperCAT," will be detailed. In the next section, the ExperCAT design will be presented. In the following section, some example runs of the system will be presented. Finally, the ExperCAT development will be summarized and suggestions for future improvements and program verification will be presented.

2. ExperCAT Design

The requirement for ExperCAT is to analyze and forecast, in the short-range, atmospheric turbulence not associated with convection. The system is also required to use satellite imagery as the primary source of information on which to base its analyses. Because the available expertise that meets these requirements applies to high-level (>18,000 feet) turbulence, the system applies only to that region.

Because the frame-based SIAMES expert system (Peak, 1989) was the genesis for turbulence forecasting at NOARL, it was first thought that ExperCAT would also be implemented using frames. SIAMES, however, involves a general analysis of all cloud features that are seen on a satellite image. Such a task is condu-

cive to the use of frame structures that embody the various aspects of the complete image analysis. ExperCAT has the more specific goal of isolating turbulence-related cloud signatures. The lines of reasoning and types of features to look for are more specific, so that rules were selected rather than frames.

The Ellrod decision tree was studied in great detail. The existing SIAMES turbulence information was examined to ensure that the decision tree included those situations as well. For the prototype, the goal-oriented approach of the Ellrod decision tree information made for a natural conversion to a backward-chaining inference system.

Based on these initial design decisions, the information from the decision tree was converted to rule form. The resulting prototype rule base contained 59 rules. An initial evaluation of the system was made by NOARL researchers, resulting in suggested improvements to the prototype. It is the improved version, ExperCAT 1.0, that is presented in this report.

For version 1.0, the rule base was expanded slightly to a total of 65 rules. An extensive explanation feature was also added. The goal is to help the user to understand the physical reasoning used to make the analysis/forecast. An added advantage is that the reasoning behind the decisions used might help the user to understand why confidence factors are low or high in given situations.

The main source of expertise for this hypertext-based explanation feature was the Ellrod decision tree manuscript (Ellrod, 1989) and an earlier, more detailed CAT paper (Ellrod, 1985).

Additional expertise came from the NTAG series (e.g., Fett et al., 1984) and from a U. S. Air Force technical report on CAT forecasting (Lee et al., 1979). The form of the ExperCAT help feature differs significantly from that in An Expert system for Shipboard Obscuration Prediction (AESOP) (Peak and Tag, 1989). In AESOP, the explanation mode invokes a comprehensive traverse of a hypertext network associated with the rules that contributed to the forecast. The reason that this form of explanation works so well in revealing the AESOP lines of reasoning is that the AESOP rules embody a cause-and-effect process. In ExperCAT, however, the CAT analysis is a progressive search for cloud signatures known to be associated with CAT. Thus, the sequence of questions does not itself reveal a physical process. Rather, each question, and the possible answers for it, progressively define a CAT likelihood. Therefore, the ExperCAT explanation feature was tailored to reveal the reasoning behind each individual question more than the sequence of questions. In ExperCAT, "Why do you ask?" and "Why are these selections important?" are the pertinent questions the user needs to ask the system.

The expert system begins with an analysis of the synoptic-scale, upper-level flow pattern. Each progressive rule narrows the evaluation of the situation with respect to the likelihood of CAT. When the system has enough information to make a judgment, the CAT analysis is presented along with a confidence factor. The turbulence categories are "Strong," "Moderate," "Light" and "No significant CAT." These intensities are from subjective turbulence reports of large commercial and military aircraft.

The confidence factors are from those included in the decision tree and are based on Ellrod's research efforts. In the next section, the function of ExperCAT 1.0 will be revealed through some example runs.

3. Example ExperCAT Runs

To demonstrate the way that ExperCAT functions, three step-by-step example runs are now discussed. These runs, for hypothetical image examples, are presented using actual ExperCAT screen displays in the Appendix.

ExperCAT begins with an introductory title screen and a text screen that explains how to select the menu items and help features (not shown). As in AESOP and SIAMES, the user moves a highlighted bar to the desired menu choice using the arrow keys and presses the carriage return to make the selection. Alternately, the first letter of the desired choice can be entered. The highlighted bar is delineated by color on the computer screen and does not appear on the figures in the Appendix. To assist the reader, an arrow is included on these figures to indicate which item is being selected. In an actual run, of course, these arrows would not appear.

To access hypertext help information about the questions being asked, the user can press the F1 key. For help about each potential selection for a given question, the user can move the highlighted bar to the desired choice and press F2.

The next screen that appears (SCREEN 1) includes the top-level decision whether to make a forecast or exit the system. Since we have just started, we enter the former. This action is

denoted on SCREEN 1 by an arrow pointing to the selection and an action in parentheses -- in this case, the carriage return, or (cr) for brevity.

The system's response is to display SCREEN 2. Here, ExperCAT attempts to define the upper-atmospheric synoptic flow pattern. In SCREEN 2, we have the user choosing the help facility for a further explanation of the question by pressing F1. A pop-up window containing the explanatory text appears at the bottom of the screen. Now suppose the user wants to know more about the three choices. He moves the highlighted bar to the first choice and presses F2 (SCREEN 3). ExperCAT responds by displaying another window of text. Notice that the explanation includes help in defining what is meant by "Straight or slightly curved flow," why this type of flow is important in relation to turbulence, and what possible exceptions to this rule might come into play. For completeness, we include the help information for the second choice (SCREEN 4) and the particularly long help screen text for choice 3 (SCREEN 5).

Assuming the user ultimately entered the first choice in SCREEN 5, ExperCAT continues the analysis (SCREEN 6). Again, we show the user asking for more information concerning the question about cirrus signatures (SCREEN 6) and then for help about the first choice (SCREEN 7). After looking at the help information for the second choice, we assume that the user chooses the first response, namely that transverse bands are present (SCREEN 8).

The next ExperCAT screen asks for a description of the curvature of the cold-air side of the cirrus SCREEN 9). The

user here asks for an explanation of the first choice, and then makes that choice. Notice that the help feature here includes information about where the turbulence is expected to occur (SCREEN 9). The analysis continues with questions about the wavelength of the curved cirrus cloud segment (SCREEN 10) and the shape of the transverse bands (SCREENS 11 and 12).

Finally, ExperCAT has narrowed the decision down and makes an analysis/forecast (SCREEN 13). As pointed out in the ExperCAT introductory screen (not shown), the CAT intensity here is that expected for large aircraft. If the user wishes a review of the selections he has made to arrive at this forecast, he can press F1 and the expert system's facts will be listed (SCREEN 14). In its present version, ExperCAT does not allow the user to change individual responses and then rerun the analysis as does AESOP (Peak and Tag, 1989). The reason for this design choice stems from the differences between the two rule base domains. AESOP performs an exhaustive analysis of potential visibility obscurations based on a fixed set of input parameters. ExperCAT, however, only asks for the information pertinent to its current line of reasoning. Thus, changing one answer usually causes all of the subsequent questions no longer to apply, and the user would have to reenter an entire, new sequence of answers anyway. For this reason, a modification feature was deemed unnecessary; the user must invoke a completely new run of ExperCAT to determine the effects of different input data. On the other hand, such a modification feature is certainly possible, and could be included if NOARL considers it necessary.

The second example run begins with the end of the previous one. When the forecast screen (SCREEN 13) is displayed, the user simply enters the carriage return to arrive again at the top-level decision screen (SCREEN 15). In this example, we choose the second type of synoptic flow -- sharply curved (SCREEN 16). Of the two types of sharply-curved flow, the user indicates that it is a trough (SCREEN 17). In SCREEN 18 the system looks for signatures that support turbulence when they occur in conjunction with a trough. The help text in SCREEN 18 elaborates on the physical connection between darkening in the water vapor channel and turbulence-production.

When the user affirms that water-vapor darkening is present, ExperCAT makes a forecast. Note that this time the forecast is accompanied by clarifying text concerning the location of the turbulence, help in establishing a confidence level, and what to look for in determining the dissipation of the turbulence (SCREEN 19).

For the third example run, we omit the top-level decision screen and proceed to the synoptic flow pattern question (SCREEN 20). This time, the last choice (hyperbolic flow) is selected. There are three possible cloud patterns associated with deformation zones (SCREEN 21). Here the user invokes the help feature (F2) to get an explanation of "delta-shaped cirrus," but then chooses the "comma cloud" selection. Because the different regions of a comma cloud have different turbulence-producing conditions, the question in SCREEN 22 narrows down the search for turbulence signatures. Further narrowing of the search is accom-

plished by the three types of synoptic situations to choose from in SCREEN 23. A further description of the comma itself occurs in SCREEN 24. Here, the help feature assists in explaining what is meant by "sheared comma." In future versions, a pictorial depiction of this, and other potentially ambiguous questions would be desirable.

The last information needed before the forecast is the sharpness of the cloud edge (SCREEN 25). Again, the help feature reveals the physical reason that this signature is important. The display of the forecast screen (SCREEN 26) ends this last example run.

4. Conclusions and Recommendations

In this paper, an expert system approach for analysis and short-term forecasting of clear air turbulence has been presented. The major source of expertise for the expert system rule base is the research of Dr. Gary Ellrod of NOAA/NESDIS.

The system described in this paper, named "ExperCAT," is version 1.0, having progressed through the design, prototype, and prototype revision stages of development. ExperCAT is rule-based, uses backward-chaining inference, and has a hypertext-based explanation/help feature. The system function is demonstrated through three example runs.

At this point, ExperCAT has not been verified using actual data because of the unavailability of CAT reports at NOARL. It is recommended that the system be verified to ensure its usability and correctness. One possible method would be to acquire a set of satellite images and CAT reports for historical cases.

Another possibility would be to use atmospheric profiler information in conjunction with real-time imagery. The author understands that such a profiler, soon to be located at Fort Ord, would be able to detect high-level CAT.

It would be desirable for the system to include diagrams or figures to assist in describing the various selections the user needs to choose between. In discussions with Buck Sampson of NOARL, the author has determined that the "PC-Paint" software in conjunction with a scanner might be used. It is recommended that this possibility be pursued. If NOARL considers it necessary, a modification/rerun feature could also be included.

The next logical step in ExperCAT development is to elicit an expert evaluation from the author of the main source of expertise used in developing the system, to ensure that the transition to an expert system has not led to the garbling or omission of key information. It is planned to send the latest version to Dr. Ellrod in hopes of obtaining his comments.

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APPENDIX

EXAMPLE EXPERCAT RUNS

SCREEN 1:

```
E X P E R C A T   Version 1.0 -- 4/10/90

        Which would you like to do?
        Make a clear air turbulence forecast <------ (cr)
        Exit from EXPERCAT
```

SCREEN 2:

```
E X P E R C A T   Version 1.0 -- 4/10/90

    Which describes the upper synoptic flow pattern? <------ (F1)
    Straight or slightly curved flow
    Sharply curved (ridge or trough)
    Hyperbolic (deformation zones)

                    EXPERCAT HELP
  I am checking the synoptic pattern because, in general, upper flow
 patterns with shorter wavelengths and more curvature are more
 conducive to extensive turbulence.  This question applies to the
 region of interest in the next few hours, and the answer can be
 determined from animated satellite imagery, upper wind charts, and/or
 forecasts.
```

SCREEN 3:

```
EXPERCAT Version 1.0 -- 4/10/90

Which describes the upper synoptic flow pattern?
Straight or slightly curved flow <------ (F2)
Sharply curved (ridge or trough)
Hyperbolic (deformation zones)

EXPERCAT HELP
  This flow pattern includes broad, smooth upper lows, ridges or
troughs and confluent jets.  In general, turbulence is less likely to
be associated with straight flow than with sharply-curved flow.  The
exception to this rule is when there are local areas of strong
vertical shears generated by jet streaks.
```

SCREEN 4:

```
EXPERCAT Version 1.0 -- 4/10/90

Which describes the upper synoptic flow pattern?
Straight or slightly curved flow
Sharply curved (ridge or trough) <------ (F2)
Hyperbolic (deformation zones)

EXPERCAT HELP
  In general, turbulence is more likely with curving jet stream
segments, mainly in conjunction with sharp troughs and ridges.
```

SCREEN 5:

E X P E R C A T Version 1.0 -- 4/10/90

Which describes the upper synoptic flow pattern?

Straight or slightly curved flow ← (cr)
Sharply curved (ridge or trough)
Hyperbolic (deformation zones) ← (F2)

EXPERCAT HELP

A deformation zone is a region of hyperbolic flow where air parcels undergo stretching along one axis and contraction in the orthogonal direction. They are the most common large-scale turbulence signature. In both visual and IR imagery, deformation zones are often marked by the location of significant cloud boundaries. If the water vapor channel is available, deformation zones can usually be identified by moisture boundaries on that image. Turbulence occurs within 2-3 degrees latitude (330 km) of the deformation boundary, both in clear air and in cirrus clouds. When the winds intersect the isotherms at a large enough angle, deformation zones are frontogenetic in nature. It is these upper-level fronts that produce the high-level turbulence.

SCREEN 6:

E X P E R C A T Version 1.0 -- 4/10/90

Do you see either of these cirrus signatures? ← (F1)

Transverse bands (IR & VIS) or billows (VIS)
Ragged poleward cirrus edge near jet with dense cirrus patches
Neither cirrus signature

EXPERCAT HELP

These cirrus signatures are important because they indicate atmospheric wind shear. In relatively straight flow, turbulence is caused by strong vertical shears. The presence of both speed and directional shear often results in wave cloud features. Strong speed shear can cause the poleward cirrus edge to become ragged or scalloped in appearance.

SCREEN 7:

```
─────────────── E X P E R C A T  Version 1.0 -- 4/10/90 ───────────────

     ───────Do you see either of these cirrus signatures?──────
     Transverse bands (IR & VIS) or billows (VIS)◄────────(F2)
     Ragged poleward cirrus edge near jet with dense cirrus patches
     Neither cirrus signature

                          ─────EXPERCAT HELP─────
  Speed and directional shear conditions often result in wave cloud
 features oriented transverse to the upper flow.  Transverse bands are
 more irregular than billows, and are more likely to be observed in
 lower resolution IR images such as those from GOES.  The presence of
 cirrus billows may indicate strong shear (Kelvin-Heimholtz)
 instability.  The longer the wavelength of the billows, the better the
 chance of significant turbulence.
```

SCREEN 8:

```
─────────────── E X P E R C A T  Version 1.0 -- 4/10/90 ───────────────

     ───────Do you see either of these cirrus signatures?──────
     Transverse bands (IR & VIS) or billows (VIS)        ◄──────(cr)
     Ragged poleward cirrus edge near jet with dense cirrus patches◄──────(F2)
     Neither cirrus signature

                          ─────EXPERCAT HELP─────
  The ragged edge occurs with speed shear caused by ageostrophic
 accelerations near a jet streak.  When turbulence occurs, wind speeds
 in the jet are usually 80 kt or greater.
```

SCREEN 9:

```
E X P E R C A T  Version 1.0 -- 4/10/90

     Describe the cold-air side of the cirrus
     Anticyclonic curvature <----------(F2,cr)
     Straight or cyclonic curvature

                         EXPERCAT HELP
  Sharp, anticyclonically-curved bulges along the jet stream cirrus
 relate to jet streaks.  The maximum winds are located near the crest
 of the cirrus bulge.  When turbulence occurs, wind speeds in the jet
 are usually 80 kt or greater.  The turbulence usually occurs from the
 crest of the bulge downwind for several hundred kilometers.  This is
 the exit region of the jet where the air parcels decelerate rapidly.
```

SCREEN 10:

```
E X P E R C A T  Version 1.0 -- 4/10/90

   How long is the wavelength of the curved segment?
   <=500 nm (e.g., 8-9 degrees of latitude)
   >500 nm (e.g., 8-9 degrees of latitude) <----------(F2,cr)

                         EXPERCAT HELP
  Less curvature is less indicative of turbulence.
```

SCREEN 11:

```
E X P E R C A T   Version 1.0 -- 4/10/90

        Which best describes the cloud bands?  <------ (F1)
        Wide, thick and carrot-shaped
        Not wide, thick and carrot-shaped

EXPERCAT HELP
  The shape of the cloud bands is important because it indicates the
degree of turbulence.  Wide, thick bands are those easily
distinguished in low resolution IR images.
```

SCREEN 12:

```
E X P E R C A T   Version 1.0 -- 4/10/90

        Which best describes the cloud bands?
        Wide, thick and carrot-shaped  <------ (F2,cr)
        Not wide, thick and carrot-shaped

EXPERCAT HELP
In general, the wider, thicker transverse bands are more likely to
contain severe turbulence, possibly due to the added presence of
thermal instability.  In these situations, the bands often have a
carrot-shaped appearance similar to that of Cb anvils.
```

SCREEN 13:

E X P E R C A T Version 1.0 -- 4/10/90

EXPERCAT FORECAST

Clear Air Turbulence: Moderate or Greater

Confidence: 70%

SCREEN 14:

E X P E R C A T Version 1.0 -- 4/10/90

EXPERCAT FORECAST (F1)

Clear Air Turbulence: Moderate or Greater

Confidence: 70%

EXPERCAT FACTS

Synoptic flow pattern is: Straight or slightly curved flow
Cirrus signature is: Transverse bands (IR & VIS) or billows (VIS)
Cold-air side of cirrus is: Anticyclonic curvature
Curved segment wavelength is: >500 nm (e.g., 8-9 degrees of latitude)
Cloud bands character is: Wide, thick and carrot-shaped

SCREEN 15:

```
E X P E R C A T   Version 1.0 -- 4/10/90

        Which would you like to do?
        Make a clear air turbulence forecast <------(cr)
        Exit from EXPERCAT
```

SCREEN 16:

```
E X P E R C A T   Version 1.0 -- 4/10/90

    Which describes the upper synoptic flow pattern?
    Straight or slightly curved flow
    Sharply curved (ridge or trough) <------(cr)
    Hyperbolic (deformation zones)
```

SCREEN 17:

```
E X P E R C A T   Version 1.0 -- 4/10/90

        Which type of sharply curved flow?
        Ridge (on south side of jet)
        Trough (preferably with strong upstream jet) ←(F2,cr)

EXPERCAT HELP
  It is also preferable that the trough have a north-south or
northeast-southwest tilt.
```

SCREEN 18:

```
E X P E R C A T   Version 1.0 -- 4/10/90

Which of these are present?
Sharp, well-defined cirrus edge near trough axis
Darkening zone in water vapor image along or upstream from trough ←(F2,cr)
Both a sharp cirrus edge and darkening zone
Neither a sharp cirrus edge nor a darkening zone

EXPERCAT HELP
  These zones are elongated bands or, in some cases, large oval gray
regions that become darker in successive images.  The darkening is
usually accompanied by cold advection and convergence in the mid- and
upper levels of the troposphere, resulting in compensating sinking
through a deep layer.  Cross-sections through such features reveal
sloping baroclinic zones (tropopause leaves or folds), indicating that
stratospheric air is descending into the upper troposphere.
```

SCREEN 19:

E X P E R C A T   Version 1.0 -- 4/10/90

EXPERCAT FORECAST

Clear Air Turbulence: Moderate or Greater

Confidence: 80%

The CAT is normally in the region of the most rapid water vapor darkening. If the darkening has persisted for at least 3 hours, there is higher confidence that turbulence is present. When the darkening ceases, turbulence diminishes.

SCREEN 20:

E X P E R C A T   Version 1.0 -- 4/10/90

Which describes the upper synoptic flow pattern?
Straight or slightly curved flow
Sharply curved (ridge or trough)
Hyperbolic (deformation zones) ←——— (cr)

SCREEN 21:

```
E X P E R C A T  Version 1.0 -- 4/10/90

Which cloud feature is present?
Comma cloud <-------------(cr)
Delta-shaped cirrus(IR/VIS, W-NW flow) <-------------(F2)
Little or no cloudiness
```

EXPERCAT HELP

These features occur in west or northwest flow and usually are not associated with developing surface lows. They also have a different appearance in the imagery since the cirrus often forms in elongated bands transverse to the flow, probably due to the presence of gravity waves. Such cirrus can appear as a triangular-shaped area known as a delta region. The appearance of these features varies considerably, depending on the availability of moisture. Turbulence occurs within 2 to 3 degrees latitude (180 nm) of the leading edge of the clouds.

SCREEN 22:

```
E X P E R C A T  Version 1.0 -- 4/10/90

Where is the forecast location with respect to the comma cloud?
Near the poleward edge of the comma head <-------------(F2,cr)
In the dry slot
Near the comma tail
```

EXPERCAT HELP

The most significant turbulence with a comma cloud deformation zone occurs in conjunction with a developing cyclone. Each of these three locations has a different set of considerations in analyzing turbulence.

SCREEN 23:

```
E X P E R C A T   Version 1.0 -- 4/10/90

      Describe the synoptic situation
  Deepening or steady-state upper-level low center <------(cr)
  Upper-level low opening into trough or filling
  Upper-level vorticity maximum with no closed low
```

SCREEN 24:

```
E X P E R C A T   Version 1.0 -- 4/10/90

      Which type of comma system is present? <------(F1)
  Full comma <------(cr)
  Sheared comma (the jet crosses over the cloud head)

                        EXPERCAT HELP
  During the comma development, the jet will sometimes continue to
push through the comma cloud and cross over the ridge line.  When this
happens, the jet location will be marked by a sharp boundary between
higher cirrus on the anticyclonic side and the lower-layer clouds
forming the comma head.
```

SCREEN 25:

E X P E R C A T Version 1.0 -- 4/10/90

Are any of these conditions present?

The cloud border is well-defined on IR or is becoming sharper with time ◄(F2,cr)
There are transverse bands or billows on VIS near the cloud edge
There is rapid (>=25kt) movement of the cloud edge toward the clear air
Two or more of these conditions
None of these conditions

EXPERCAT HELP

A sharp cloud edge indicates strong convergence and a sharp thermal boundary, both indicators of turbulence.

SCREEN 26:

E X P E R C A T Version 1.0 -- 4/10/90

EXPERCAT FORECAST

Clear Air Turbulence: Moderate or Greater

Confidence: 70%

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. Agency Use Only (Leave blank).	2. Report Date.	3. Report Type and Dates Covered.
	March 1991	Final

4. Title and Subtitle.
ExperCAT: An Expert System for Analysis and Short-Term Prediction of Clear Air Turbulence

5. Funding Numbers.
Program Element No. 62435N
Project No. RM35G80
Task No. 3
Accession No. DN656766

6. Author(s).
J.E. Peak

7. Performing Organization Name(s) and Address(es).
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Naval Oceanographic and Atmospheric Research Laboratory
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8. Performing Organization Report Number.
NOARL Technical Note 101

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Naval Ocean Systems Center
Code 54
San Diego, CA 92152-5000

10. Sponsoring/Monitoring Agency Report Number.
NOARL Technical Note 101

11. Supplementary Notes.

12a. Distribution/Availability Statement.
Approved for public release; distribution is unlimited.

12b. Distribution Code.

13. Abstract *(Maximum 200 words).*

An expert system approach to the analysis and short-term prediction of clear air turbulence (CAT) is presented. CAT is defined here as nonconvective turbulence occurring above 18,000 feet. ExperCAT is rule-based, contains a total of 65 rules and has extensive help and explanation features. The system's analysis procedure is to guide a human observer in identifying cloud signatures known to be associated with CAT. ExperCAT forecasts include an estimate of the turbulence intensity and a confidence factor. The user can optionally view the selections entered to arrive at the forecast. Three step-by-step example runs are provided.

14. Subject Terms.
Turbulence; Artificial intelligence; Clear air turbulence; CAT; Satellite imagery; Expert systems

15. Number of Pages. 34

16. Price Code.

17. Security Classification of Report.	18. Security Classification of This Page.	19. Security Classification of Abstract.	20. Limitation of Abstract.
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	Same as report

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102